

# Weak equivalence classes of complex vector bundles

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## Abstract

For any complex vector bundle  $E^k$  of rank  $k$  over a manifold  $M^m$  with Chern classes  $c_i \in H^{2i}(M^m, \mathbb{Z})$  and any non-negative integers  $l_1, \dots, l_k$  we show the existence of a positive number  $N(k, m)$  and the existence of a complex vector bundle  $\hat{E}^k$  over  $M^m$  whose Chern classes are  $N(k, m) \cdot l_i \cdot c_i \in H^{2i}(M^m, \mathbb{Z})$ . We also discuss a version of this statement for holomorphic vector bundles over projective algebraic manifolds.

MSC: 55R25, 55R37

*Key words:* Chern classes, complex Grassmannians, weak equivalence

## 1 Introduction.

The study of complex vector bundles of rank  $k$  over a manifold  $M^m$  can be reduced to the study of mappings from  $M^m$  to the classifying space  $Gr_k(\mathbb{C}^\infty) = BU_k$ . Certain equivalence relations of complex vector bundles lead us to study **stable mappings** of  $BU_k$  to itself.

We call a **map**  $g : BU_k \rightarrow BU_k$  **stable**, if the restriction of  $g$  to any subspace  $Gr_k(\mathbb{C}^N)$  sends  $Gr_k(\mathbb{C}^N)$  to some Grassmannian

$Gr_k(\mathbb{C}^{f(N)})$ , moreover  $g^*(c_k) = \lambda \cdot c_k$  for some positive  $\lambda$ . Here  $c_k$  denotes the top Chern class of the universal bundle over  $BU_k$ .

Two maps  $f_1, f_2 : M^m \rightarrow BU_k$  are said to be in one **stable equivalence class**, if  $f_1 = g \circ f_2$  for some stable map  $g : BU_k \rightarrow BU_i$ . Two complex vector bundles  $E_1^k$  and  $E_2^k$  are said to be in the same **weak equivalence class**, if the corresponding homotopy classes of classifying maps contain maps in the same stable equivalence class. Two complex vector bundles  $E_1^k$  and  $E_2^k$  are called **Chern weakly equivalent**, if their top Chern classes are differed by a positive constant. Clearly vector bundles in the same weak equivalence class are Chern weakly equivalent. Zero sections of Chern weakly equivalent vector bundles realize the same homology classes up to a positive constant.

**1.1. Theorem.** *For any complex vector bundle  $E^k$  of rank  $k$  over a manifold  $M^m$  with the Chern classes  $c_i \in H^{2i}(M^m, \mathbb{Z})$  and any non-negative integers  $l_1, \dots, l_k$ ,  $l_k > 0$ , there exists a vector bundle  $\hat{E}^k$  in the same weak equivalence class with  $E^k$ , and a positive number  $p(k, m)$  such that the Chern classes  $c_i(\hat{E}^k)$  are  $N(k, m) \cdot l_i \cdot c_i \in H^{2i}(M, \mathbb{Z})$ .*

As a corollary of Theorem 1.1 and Thom's theorem [Thom1954, Theorem II.25] (a detailed proof of this theorem is given in [Le2005b] and in the Appendix below) we get

**1.2. Corollary.** [Le2005, Proposition 2.7] *Suppose that  $M^m$  is an orientable differentiable manifold. For any  $c \in H^{2k}(M^m, \mathbb{Z})$  there exists a number  $N > 0$  such that there exists a complex vector bundle  $E^k$  of rank  $k$  over  $M$  whose top Chern class is  $N \cdot c$  and all other lower Chern classes are zero.*

We can think of Theorem 1.1 together with the Thom theorem as a version of the Atiyah-Hirzebruch theorem about isomorphism between the two rings  $K(M^m) \otimes \mathbb{Q}$  and  $H^{even}(M^m, \mathbb{Q})$  via the Chern character [A-H1961] which implies that giving an element of  $K(M^m) \otimes \mathbb{Q}$  is the same as giving an element in  $H^{even}(M^m, \mathbb{Q})$ . Our Theorem 1.1 concerns vector bundles with a given dimension on  $M^m$ . I did not give enough details to the proof of Proposition 2.7 in [Le2005], so now the proof of Theorem 1.1 should compensate that deficit.

For  $i \leq k$  there is a projection map  $p$  from  $B_{U(i)}$  to  $B_{U(k)}$  with fiber  $U(k)/U(i)$  such that  $p^*(c_i) = c_i$ . Another consequence of a proof of Theorem 1.1 is

**1.3. Corollary.** *There are maps  $g_{k,i}^m : Gr_k(\mathbb{C}^m) \rightarrow Gr_i(\mathbb{C}^l) \rightarrow B_{U(i)} \rightarrow B_{U(k)}$  such that  $g_{k,i}^N(c_j) = p(k, \binom{m}{k}) \cdot \delta_j^i \cdot c_j$  for  $1 \leq i, j \leq k$ .*

In the third section of this note we discuss the problem of extending the notion of weak equivalence to the category of holomorphic vector bundles over projective algebraic manifolds. Two holomorphic vector bundles  $E^k$  and  $F^k$  over a complex manifold  $M^m$  are said to be **Kähler weakly equivalent**, if there are two holomorphic line bundles  $L_1$  and  $L_2$  over  $M^m$  such that  $E^k \otimes L_1$  and  $F^k \otimes L_2$  are Chern weakly equivalent.

It is well-known that the Hodge conjecture is equivalent to the statement that the Hodge group  $H^{p,p}(M, \mathbb{Q}) := H^{2p}(M, \mathbb{Q}) \cap H^{p,p}(M, \mathbb{C})$  is generated by the top Chern classes of holomorphic vector bundle of rank  $p$  on a projective algebraic manifold  $M^n$  (see e.g. [Voisin2002]). A motivation for the notion of Kähler weak equivalence is Lemma 3.1 below which states that any holomorphic vector bundle on a projective algebraic is Kähler weak equivalent to a holomorphic vector bundle such that the homotopy class of its classifying maps contains a holomorphic map. With this on hand, we speculate about reduction of the Hodge conjecture to the existence of certain holomorphic maps which may be obtained by using on the one hand Zucker and Saito results on the existence of normal functions associated to primitive Hodge cocycles in middle dimensions and on the other hand Siu's technique on harmonic maps.

For the convenience of the reader I include in this note an appendix which re-exposes the detailed proof of Thom's theorem in [Le2005b], which now has a simpler form, since this proof is very close to our proof of Theorem 1.1.

## 2 Proof of Theorem 1.1.

*Proof of Theorem 1.1.* Denote by  $\gamma^k$  the tautological bundle over the Grassmannian  $Gr_k(\mathbb{C}^N)$  (we assume that  $N = \infty$  or  $N$  is sufficiently large as it shall be specified later). Since  $E^k$  is the pull-back of  $\gamma$  via a classifying map  $f : M^m \rightarrow Gr_k(\mathbb{C}^N)$ , it suffices to prove Theorem 1.1 for the case  $M = Gr_k(\mathbb{C}^N)$ ,  $E^k = \gamma^k$  and  $N$  is sufficiently large, and after that we use the classifying map  $f$  to take back the obtained bundle to  $M^m$ .

Let us denote by  $K(\mathbb{Z}, n)$  the Eilenberg-McLane space and by  $\tau^n$  the fundamental class of  $K(\mathbb{Z}, n)$ . Let  $f_k^N : Gr_k(\mathbb{C}^N) \rightarrow K(\mathbb{Z}, 2k)$  be

a classifying map for  $c_k(\gamma) \in H^{2k}(M, \mathbb{Z})$ , i.e.  $(f_k^N)^*(\tau^{2k}) = c_k(\gamma) \in H^{2k}(M, \mathbb{Z})$ .

Let  $F_N^n$  be a map from  $K(\mathbb{Z}, n) \rightarrow K(\mathbb{Z}, n)$  such that  $F_N^n(\tau^n) = N\tau^n$ . The existence of a map  $F_N^n$  is ensured by the fact that  $K(\mathbb{Z}, n)$  is the classifying space for  $(H^*n, \mathbb{Z})$ . Clearly  $F_N^n$  is defined uniquely up to homotopy.

**2.1. Lemma.** [Thom1954, Lemma II.22] *For any finite abelian group  $G$  of order  $N$  the endomorphism  $(F_N^n)^* : H^*(K(\mathbb{Z}, n), G)$  is trivial.*

(Lemma 2.1 follows directly from Cartan's result which states that the algebra  $H^*(K(\mathbb{Z}, n), \mathbb{Z}_p)$  is generated by iteration of the Steenrod squares of  $\tau^n$ ).

Denote by  $Y^q$  the  $q$ -skeleton of a CW-complex  $Y$ . Clearly  $\pi_k(K^q(\mathbb{Z}, n)) = \pi_k(K(\mathbb{Z}, n))$  for any  $k \leq q$ .

**2.2. Proposition.** *Suppose that  $Y$  is a simplicial space whose  $q$ -skeleton  $Y^q$  is compact for each  $q$ . Let the free component of  $\pi_k(Y)$  be isomorphic to  $\mathbb{Z}$  with a generator  $t$  and let  $Q$  be an integer such that  $Q \geq k$ . If for all  $Q \geq q \geq k$  the group  $H^{q+1}(K(\mathbb{Z}, k), \pi_q(Y))$  is finite, then there exists a map  $G_Q : K^Q(\mathbb{Z}, k) \rightarrow Y$  such that  $(G_Q)_*(\pi_k(K^Q(\mathbb{Z}, k))) = \langle N(Q, k)t \rangle_{\otimes \mathbb{Z}} \subset \pi_k(Y)$ .*

Proposition 2.2 is a reformulation of Lemma II.24 in [Thom1954], where Thom did not explicitly introduce the parameter  $Q$ . We quickly recall his argument, adapted to this new reformulation. We prove Proposition 2.2 by induction on the dimension  $Q \geq k$ . Clearly Proposition 2.2 for  $Q = k$  is trivial, since  $K^k(\mathbb{Z}, k) = S^k$ .

Suppose that we have constructed a map  $G_Q$  for  $Q \geq k$ .

Now we put

$$G_Q^1 = F_N^k \circ G_Q,$$

where  $F_N^k$  is the map in Lemma 2.1. By theorem of simplicial approximation we can assume that  $F_N^k$  sends  $K^q(\mathbb{Z}, k)$  to  $K^q(\mathbb{Z}, k)$  for each  $Q \geq q \geq k$ .

Since the obstruction to an extension of  $G_Q^1$  to  $K^{Q+1}(\mathbb{Z}, k)$  lies in the group  $F_N^*(H^{q+1}(K(\mathbb{Z}, k), \pi_q(Y)))$  which is trivial by Lemma 2.1, we shall put  $G_{Q+1}$  as an extension of  $G_Q^1$  to  $K^{Q+1}(\mathbb{Z}, k)$ . This completes the induction step for the proof of Proposition 2.2.

**2.3. Lemma.** *Suppose that  $N \geq 2l + 1$ . Then the space  $Gr_l(\mathbb{C}^N)$  satisfies the condition for  $Y$  with  $Q = N$  and for all  $k = 2r$ , if  $1 \leq r \leq l$ , in Proposition 2.2.*

*Proof.* To prove Lemma 2.3 it suffices to verify the following three identities

$$(2.3.1) \quad \pi_{2r}(Gr_l(\mathbb{C}^N)) \otimes \mathbb{Q} = \mathbb{Q}, \text{ for all } 1 \leq r \leq l$$

$$(2.3.2) \quad \pi_q(Gr_l(\mathbb{C}^N)) \otimes \mathbb{Q} = 0, \text{ for all other } q \leq N$$

$$(2.3.3) \quad H^{q+1}(K(\mathbb{Z}, 2l), \pi_q(Gr_l(\mathbb{C}^N)) \otimes \mathbb{Q}) = 0, \forall q.$$

To prove (2.3.1) we consider the following exact sequence

$$(2.3.4) \quad \pi_q(U_l \times U_{N-l}) \rightarrow \pi_q(U_N) \rightarrow \pi_q(Gr_l(\mathbb{C}^N)) \rightarrow \pi_{q-1}(U_l \times U_{N-l})$$

which also remains exact after tensoring with  $\mathbb{Q}$ . To save the notation we shall consider this exact sequence as of that of rational homotopy groups.

To prove (2.3.2) we have to consider several cases for  $q$ . For  $2 \leq q = 2r \leq 2l$  the exact sequence (2.3.4) implies the equality (2.3.1), since  $\pi_{2r}(U_N) \otimes \mathbb{Q} = 0$ ,  $\pi_{2r-1}(U_m) \times \mathbb{Q} = \mathbb{Q}$  for  $r \leq m$ , and taking into account that the kernel of the map

$$i : \mathbb{Q} \oplus \mathbb{Q} = \pi_{2r-1}(U_l \times U_{N-l}) \otimes \mathbb{Q} \rightarrow \pi_{2r-1}(U_N) \times \mathbb{Q} = \mathbb{Q}$$

is equal to  $\mathbb{Q}$ .

Now let us consider the exact sequence (2.3.4) for  $2l + 1 \leq q \leq N$ . We know [Spanier1966, 9.7] that  $\pi_q(U_l \otimes U_{N-l}) \otimes \mathbb{Q} = \pi_q(U_{N-l}) \otimes \mathbb{Q}$  and taking into account the fact that the map

$$i : \mathbb{Q} = \pi_q(U_l \times U_{N-l}) \otimes \mathbb{Q} \rightarrow \pi_q(U_N) \otimes \mathbb{Q}$$

is isomorphism. Taking into account the fact that  $\pi_q(U_{N-l}) \otimes \mathbb{Q}$  vanishes if  $q$  is even, we get

$$\pi_q(Gr_l(\mathbb{C}^N)) = \ker(\pi_{q-1}(U_l \times U_N) \rightarrow \pi_{q-1}(U_N)) = 0$$

which implies (2.3.2) for  $2l + 1 \leq q \leq N$ .

Finally to verify (2.3.2) for  $q$  odd and less than  $2l$  we notice that the map  $\pi_q(U_l \times U_{N-l}) \rightarrow \pi_q(U_N)$  is surjective, hence  $\pi_q(Gr_l(\mathbb{C}^N)) = \pi_{q-1}(U_l \times U_{N-l}) = 0$ .

The last statement (2.3.3) follows from (2.3.1) for  $q = 2l$ , and it follows from (2.3.2) for all other and taking into account the fact that  $H^*(K(\mathbb{Z}, 2l), \mathbb{Q}) = \mathbb{Q}[x]$ ,  $\dim x = 2l$ . The last fact is obtained by Serre and Cartan (see e.g. [F-F, 3.25] for an exposition. In fact this computation of  $H^*(K(\mathbb{Z}, 2l), \mathbb{Q})$  can be easily obtained by using induction method and by using the cohomology spectral sequence associated with the fibration  $K(\mathbb{Z}, n-1) \cong \Omega K(\mathbb{Z}, n) \rightarrow K(\mathbb{Z}, n)$ , whose fiber is contractible.)  $\square$

*Continuation of the proof of Theorem 1.1.*

For  $N \geq 2k+1$  and for all  $2 \leq i \leq k$  Proposition 2.2 and Lemma 2.3 give us a map

$$G_{k,i}^N : K^N(\mathbb{Z}, 2i) \rightarrow Gr_k(\mathbb{C}^N)$$

such that  $(G_{k,i}^N)_*(w_i) = \alpha(N, k, i)t_i$ , where  $w_i$  is a generator of  $\pi_{2k}(K^N(\mathbb{Z}, 2i)) = \mathbb{Z}$  and  $t_i$  is a generator of  $\pi_i(Gr_k(\mathbb{C}^N)) \otimes \mathbb{Q}$ . Since  $H^*(Gr_k(\mathbb{C}^N), \mathbb{Z})$  is generated by  $c_i(\gamma), i = \overline{1, k}$ , [Borel1953], we have

$$(2.4) \quad \langle c_i, t_i \rangle = A_i \neq 0$$

because  $t_i$  is the generator of the free part of  $\pi_{2i}(Gr_k(\mathbb{C}^N))$ . (To show that  $A_i \neq 0$  we consider the exact sequence (2.3.4). We see easily that the image of  $\rho(t_i)$  via embedding  $G_k(\mathbb{C}^N) \rightarrow G_k(\mathbb{C}^\infty)$  is also a generator of  $\pi_i(Gr_k(\mathbb{C}^\infty))$ . Applying the  $\mathcal{C}$ -version of the Whitehead theorem [Serre1953, Theorem III.3] to  $BU_k$  and the product  $K(\mathbb{Z}, 2) \times \cdots \times K(\mathbb{Z}, 2k)$  we notice that

$$\langle c_i, i(t_i) \rangle = A_i \neq 0$$

which pull back to  $G_k(\mathbb{C}^N)$  must also hold.) Thus

$$(2.5) \quad (G_{k,i}^N)^*(c_i) = \alpha(N, k, i) \cdot A_i \cdot \tau^{2i}.$$

We can assume that  $A_i$  is positive by choosing appropriate orientation of the generator  $t_i$ .

*Completion of the proof of Theorem 1.1.*

Denote by  $\lambda_{k,i}^N$  the classifying map from  $G_k(\mathbb{C}^N)$  to  $K(\mathbb{Z}, 2i)$  for  $c_i \in H^{2i}(G_k(\mathbb{C}^N), \mathbb{Z})$ , i.e.

$$\lambda_{k,i}^N(\tau^{2i}) = c_i.$$

We can assume that  $\lambda_{k,i}^N(G_k(\mathbb{C}^N)) \subset K^{2k(N-k)}(\mathbb{Z}, 2i)$ . For each  $i$  denote by  $s(2i)$  the smallest positive number such that for any  $j \leq i-1$  and any  $c \in H^{2j}(K(\mathbb{Z}, 2i), \mathbb{Z})$  we have  $s(2i) \cdot c = 0$ . By a theorem of Serre and Cartan mentioned above (see [F-F3.25]) there exists such a number  $s(2i)$  for all  $i$ . Let  $p(N, k)$  be the smallest integer, such that for all  $1 \leq i \leq k$  we have

$$p(N, k) = \alpha(N, k, i) \cdot A_i \cdot s(2i) \cdot \beta(N, k, i)$$

for some positive integer  $\beta(N, k, i)$ . We shall construct a map  $T : Gr_k(\mathbb{C}^N) \rightarrow Gr_k(\mathbb{C}^{2k(N-k)})$  such that

$$(2.6) \quad T^*(c_k) = p(N, k) \cdot l_k \cdot c_k.$$

Then, taking into account of the functoriality of the Chern classes, the bundle  $\hat{E}^k$  defined by  $\hat{E}^k = (f \circ T)^* \gamma_k$  satisfies the condition of Theorem 1.1. Our map  $T$  is the composition of

$$(f_{k,1}^N, f_{k,2}^N, \dots, f_{k,k}^N)$$

where

$$f_{k,i}^N = G_{k,i}^N \circ \overline{F_{l_i \cdot \beta(N, k, i)}^{2i}} \circ \lambda_{k,i}^N,$$

where  $\overline{F_{l_i \cdot s(2i) \cdot \beta(N, k, i)}^{2i}}$  denotes the restriction of the map  $F_{l_i \cdot s(2i) \cdot \beta(N, k, i)}^{2i}$  to  $K^{2k(N-k)}(\mathbb{Z}, 2i)$  (see Lemma 2.1). Because of our choice of  $s(2i)$  and taking into account of Lemma 2.1, the map  $T$  satisfies the condition (2.6).  $\square$

### 3 Kähler weak equivalence

In this section we discuss some problems which arise in extending the results in the previous section to the category of holomorphic bundles over complex or projective algebraic manifolds.

We would like to show another necessity for the notion of Kähler weak equivalence notion. Let  $E^k$  be a complex vector bundle over a

complex manifold  $M^n$  and  $[f_{E^k}]$  be a the homotopy class of a classifying map  $M \rightarrow Gr_k(\mathbb{C}^N)$  for  $E^k$ . Clearly if  $[f_{E^k}]$  contains a holomorphic map, then  $E^k$  has a holomorphic structure. But the converse statement is not true, because the pull back of of any positive  $(1, 1)$ -cohomology classes via holomorphic map is also a non-positive  $(1, 1)$ -cohomology class. On the other hand there are many holomorphic vector bundles whose first Chern class is a negative  $(1, 1)$ -class. We shall say that a holomorphic vector bundle is **positive**, if its classifying class contains a holomorphic map.

**3.1. Lemma.** *Suppose that  $M^m$  is a projective algebraic manifold and  $E^k$  is a holomorphic vector bundle over  $M^m$ . Then  $E^k$  is Kähler weakly equivalent to a positive holomorphic vector bundle.*

*Proof.* This Lemma is a consequence of an well-known fact (see e.g. [G-H1978, Chapter 1, §5]) that a tensor of  $E^k$  with a some power  $L^{\otimes l}$  of a Kähler line bundle  $L$  admits enough holomorphic sections which serve as a holomorphic map from  $M^m$  to  $Gr_k(\mathbb{C}^N)$ , where  $\mathbb{C}^N$  is a subspace in  $H^0(M^m, \mathcal{O}(E^k))$ . Furthermore, this holomorphic map is a classifying map for the holomorphic bundle  $E \otimes L^{\otimes k}$ , see e.g. [G-H1978, Chapter 3, §3].  $\square$

We are lead by Lemma 3.1 to study the space  $Hol(M^m, BU_k)$  of holomorphic maps from  $M^m \rightarrow BU_k$ . Denote by  $Hodge(M)$  the group  $H^{p,p}(M, \mathbb{Q})$  and by  $[Hodge(M)]$  the quotient class  $Hodge(M)/\mathbb{Q}$  by multiplication. We define then a map  $C : Hol(M^m, BU_k) \rightarrow [Hodge^k(M)]$  by  $C(f) = [f^*(c_k)]$ . Then the Hodge conjecture is true, if and only if the image of map  $C$  contains some neighborhood of a point  $[P] \in [Hodge^k(M)]$  for some  $P$  being a power of a Kähler class. The problem in this naive thinking is that,  $C$  maps a connected component of  $Hol(M^m, BU_k)$  to one point. It seems that we need to work every thing (including the Hodge theory) from the beginning in the field of rationals. Another possible way to do with is mentioned in the introduction.

## 4 Appendix: A proof of a theorem of Thom.

Let  $M^n$  be an orientable differentiable manifold.



**A.1. Theorem** [Thom1954 Theorem II.25]. *For each cohomology class  $z \in H^k(M^n, \mathbb{Z})$  there exists a number  $N(k, n)$  such that the class  $N(k, n) \cdot z$  is the Euler class of an orientable vector bundle on  $M^n$ . If  $k = 2l$ , then there exists a number  $N_1(k, n) \geq N(k, n)$  such that the class  $N_1(k, n) \cdot z$  is a top Chern class of a complex vector bundle on  $M^n$ .*

Thom gave a detailed proof of Theorem A.1 for  $G = SO(k)$ . He noticed that his proof also works for  $G = U(k)$  or  $Sp(k)$ . Since we use Thom's theorem for  $G = U(k)$  in [Le2005] as well as for our statement in the introduction on the relation with Atiyah-Bott theorem, we feel a need for a detailed proof of Thom's theorem A.1 in this case.

*Proof of Theorem A.1.* Suppose that  $u \in H^{2k}(M^m, \mathbb{Z})$ . Then there is a map

$$f : M^m \rightarrow K(\mathbb{Z}, 2k)$$

such that  $f^*(\tau^{2k}) = u$ , where  $\tau^{2k}$  is the fundamental class of  $H^k(K(\mathbb{Z}, 2k), \mathbb{Z})$ . Moreover we can assume that  $f(M^m) \subset K^m(\mathbb{Z}, 2k)$ , where  $K^q(\mathbb{Z}, 2k)$  is the  $q$ -skeleton of the Eilenberg-McLane space  $K(\mathbb{Z}, 2k)$ . To prove Theorem A.1 it suffices to find a map

$$h : K^m(\mathbb{Z}, 2k) \rightarrow B_{U(k)}$$

such that for some positive number  $N_1(k, m)$  we have

$$(2.2) \quad h^*(c_k) = N_1(k, m)j^*(\tau^{2k}),$$

where  $e_{2k} = c_k$  is the top Chern class of the universal bundle  $V_{U(k)}$  over  $B_{U(k)}$  and  $j$  is the embedding  $K^m(\mathbb{Z}, 2k) \rightarrow K(\mathbb{Z}, 2k)$ .

To find a map  $h$  we apply Proposition 2.1. The main issue is to verify that the space  $BU_k$  satisfies the condition for the space  $Y$  in Proposition 2.1. We use the same argument as that in our proof of Lemma 2.3, actually the case of  $BU_k$  is easier, since the related exact sequences are simpler, The required map  $h$  can be constructed in the same way as we did in our proof of Lemma 2.2 .)  $\square$

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